CALCULATION OF SENSOR ARRAY INDUCED PHASE ANGLE INDEPENDENT FROM DEMODULATION PHASE OFFSET OF PHASE GENERATED CARRIER

TECHNICAL FIELD

The invention relates generally to signal processing and more particularly to demodulation of signals from fiber optic sensor arrays.

BACKGROUND

Fiber optic sensor arrays of a time division multiplexed ("TDM") system are often used to measure a change in a parameter, for example, acoustic vibration, fluid pressure variations, acceleration, and magnetic field intensity. The fiber optic sensor array employs a phase generated carrier with a period T to measure the change in the parameter at a given sampling rate. The fiber optic sensor array converts a phase angle associated with the parameter to an amplitude variation on an output pulse of light.

The phase angle is measured through various demodulation techniques of the output pulse. Typical demodulation techniques employ a quadrature component Q and an in-phase component I of the output pulse. The quadrature component Q corresponds to a sine of the phase angle, and the in-phase component I corresponds to a cosine of the phase angle. An arctangent of the ratio Q/I is equal to the phase angle. The magnitude of the change in the parameter can then be calculated from the change in the phase angle.

Calculation of the quadrature component Q and the in-phase component I requires multiple samples of the output pulse at specific intervals of the phase generated carrier. A period of the phase generated carrier is significantly longer than a period of the output pulse. The longer period of the phase generated carrier requires the samples to span several output pulses to obtain each required interval of the phase generated carrier. The longer period of the phase generated carrier reduces the sampling rate of the demodulation technique.

High-speed phase generated carriers (e.g., a frequency greater than 1MHz, or a period less than 1000 nanoseconds) do not permit the precise control of a demodulation phase offset β associated with the phase generated carrier. One shortcoming of the demodulation techniques is that a variation in the demodulation phase offset β from a fixed value reduces the accuracy of the demodulation techniques.

Thus, a need exists for reduced dependency on demodulation phase offsets for demodulation techniques of fiber optic sensor arrays that employ phase generated carriers.

SUMMARY

The invention in one embodiment encompasses a method. A sensor array employs a parameter to induce a time-varying phase angle φ on an optical signal that comprises a phase generated carrier with a demodulation phase offset β. The phase angle φ is calculated independently of the demodulation phase offset β.

Another embodiment of the invention encompasses an apparatus. A sensor array employs a parameter to induce a time-varying phase angle φ on an optical signal that comprises a phase generated carrier with a demodulation phase offset β. The apparatus comprises a processor component that calculates the phase angle φ independent from the demodulation phase offset β.

A further embodiment of the invention encompasses an article. A sensor array employs a parameter to induce a time-varying phase angle φ on an optical signal that comprises a phase generated carrier with a demodulation phase offset β. The article includes one or more computer-readable signal-bearing media. The article includes means in the one or more media for calculating the phase angle φ independently of the demodulation phase offset β.

DESCRIPTION OF THE DRAWINGS

Features of exemplary implementations of the invention will become apparent from the description, the claims, and the accompanying drawings in which:

FIG. 1 is a representation of one exemplary implementation of an apparatus that comprises one or more lasers, one or more optical switches, one or more phase modulators, one or more sensor arrays, one or more optical receivers, and one or more processor components for calculating a phase angle of an optical signal independently of a demodulation phase offset.

FIG. 2 is a representation of an exemplary plot of one or more interference pulses for the exemplary implementation of FIG. 1.

FIG. 3 is a representation of one exemplary set of calculations for the exemplary implementation of FIG. 1.

FIG. 4 is a representation of another exemplary set of calculations for the exemplary implementation of FIG. 1.

FIG. 5 is an exemplary plot of an accuracy of a prior art demodulation technique that is dependent on a demodulation phase offset.

FIG. 6 is an exemplary plot of an accuracy of the exemplary implementation of FIG. 1.

FIG. 7 is a second exemplary plot of the accuracy of the exemplary implementation of FIG. 1.

DETAILED DESCRIPTION

Turning to FIG. 1, an apparatus 100 in one example comprises a plurality of components such as computer software and/or hardware components. A number of such components can be combined or divided in the apparatus 100. An exemplary component of the apparatus 100 employs and/or comprises a set and/or series of computer instructions written in or implemented with any of a number of programming languages, as will be appreciated by those skilled in the art.

Referring to FIG. 1, the apparatus 100 in one example comprises one or more lasers 102, one or more optical switches 104, one or more phase modulators 106, one or more sensor arrays 108, one or more optical receivers 110, and one or more processor components 112. In one example, the apparatus 100 demodulates an optical signal to measure a change in a parameter, as described herein. The laser 102 in one example comprises a continuous wave laser. The laser 102 generates and sends an optical signal through the optical switch 104 and the phase modulator 106 to the sensor array 108.

The optical switch 104 in one example comprises a time division multiplexed ("TDM") switch. The optical switch 104 gates the optical signal such that the optical signal

comprises a stream of optical pulses. The phase modulator 106 impresses a phase generated carrier ("PGC") 114 on the stream of optical pulses. For example, the laser 102, the optical switch 104, and the phase modulator 106 cooperate to create one or more optical pulses 116 that comprise the phase generated carrier 114, as will be understood by those skilled in the art. The optical pulse 116 comprises a period T_{pulse}. The period T_{pulse} in one example is approximately between 100 nanoseconds and 1000 nanoseconds. The phase generated carrier 114 in one example comprises a period T_{pgc} and a modulation depth of M. The period T_{pgc} comprises a relationship with a frequency $f_{pgc} = 1 / T_{pgc}$, as will be understood by those skilled in the art. The frequency f_{pgc} in one example is approximately between 2 MHz and 20 MHz. The phase generated carrier 114 is associated with a demodulation phase offset β. The phase generated carrier 114 creates a time-varying phase angle equal to

$$\mathrm{M} \cdot \sin\left(\frac{2\pi \cdot \mathrm{t}}{\mathrm{T}_{pgc}} + \beta\right).$$

The sensor array 108 in one example comprises one or more sensors 124, 126, and 128, for example, mismatched path interferometers. The sensor array 108 splits the optical pulse 116 into one or more optical pulses 118, 120, and 122, for example, one pulse per sensor. The optical pulses 116, 118, 120, and 122 in one example are substantially the same. The sensors 124, 126, and 128 of the sensor array 108 receive the optical pulses 118, 120, and 122, respectively. The sensors 124, 126, and 128 of the sensor array 108 in one example employ one or more parameters and the optical pulses 118, 120, and 122 to create one or more respective interference pulses 130, 132, and 134. Exemplary parameters comprise acoustic vibration, fluid pressure variations, acceleration, and magnetic field intensity. For example, the sensor 124 splits the optical pulse 118 into a first portion and a second portion. The sensor 124 employs the parameter to induce a time-varying phase angle φ on the first portion of the optical pulse 118, relative to the second portion of the optical pulse 118. The

sensor 124 recombines the first portion of the optical pulse 118 with the second portion of the optical pulse 124 to create the interference pulse 130. A time-varying amplitude variation of the interference pulse 130 represents the time-varying phase angle φ between the first portion and the second portion of the optical pulse 118.

The optical pulses 116 comprise an intermediary spacing such that the interference pulses 130, 132, and 134 comprise a relatively small spacing, for example, a high duty cycle, as described herein. The interference pulses 130, 132, and 134 comprise a period substantially equal to the period T_{pulse} of the optical pulse 116. The sensor array 108 sends the interference pulses 130, 132, and 134 to the optical receiver 110 in a pulse train 136, for example, in a serial fashion. For example, the optical pulse train 136 comprises the interference pulses 130, 132, and 134.

The optical receiver 110 in one example comprises one or more photodiodes 138. In a further example, the optical receiver 110 comprises a transimpedance amplifier 140. The optical receiver 110 in one example comprises a polarization diversity receiver system (not shown), as defined in U.S. Patent No. 5,852,507, assigned to the assignee of the present invention. The optical receiver 110 receives the optical pulse train 136. The optical receiver 110 then creates one or more respective analog electrical signals that represent the interference pulses 130, 132, and 134 from the optical pulse train 136. For example, the optical receiver 110 converts a magnitude of power of the optical pulse train 136 to a voltage signal.

The processor component 112 in one example comprises a digital signal processor. In a further example, the processor component 112 comprises an analog-to-digital converter component 142. The processor component 112 in one example comprises an instance of a computer-readable signal-bearing media 144, as described herein. The analog-to-digital converter component 142 converts the analog electrical signal from the optical receiver 110

into a digital signal. The processor component 112 in one example serves to sense a change in the parameters by employing the time-varying amplitude variation of the interference pulses 130, 132, and 134 to calculate the time-varying phase angle φ.

An illustrative description of exemplary operation of the apparatus 100 is presented, for explanatory purposes. The laser 102, the optical switch 104, and the phase modulator 106 cooperate to create the one or more optical pulses 116. The sensor array 108 splits the optical pulse 116 into the optical pulses 118, 120, and 122. The sensors 124, 126, and 128 employ the parameters and the optical pulses 118, 120, and 122 to create the interference pulses 130, 132, and 134. The sensor array 108 sends the interference pulses 130, 132, and 134 as the optical pulse train 136 to the optical receiver 110.

The optical receiver 110 creates an analog electrical signal that represent the one or more interference pulses 130, 132, and 134. For example, the analog electrical signal is defined as s(t, M, β, φ):

$$s(t, M, \beta, \varphi) = A + B \cdot \cos\left(M \cdot \sin\left(\frac{2\pi \cdot t}{T_{pgc}} + \beta \right) + \varphi \right),$$

where A is an average signal level, B is an interference term signal level, M is the modulation depth, T_{pgc} is the period of the phase generated carrier, β is the demodulation phase offset, and φ is the phase angle. The phase angle of s(t, M, β, φ) comprises a first portion due to the phase generated carrier, $M \cdot \sin\left(\frac{2\pi \cdot t}{T_{pgc}} + \beta \right)$, and a second portion due to the parameter, φ, as will be understood by those skilled in the art.

The analog-to-digital converter component 142 in one example converts the analog electrical signal from the optical receiver 110 into a digital signal that represents the interference pulse 130. The processor component 112 obtains a plurality of samples S_n, n = 0

to x, of the interference pulse 130 from the digital signal. The processor component 112 obtains the plurality of samples S_n at time intervals Δt over a period T_s. The period T_s in one example is substantially equal to the period T_{pgc} of the phase generated carrier 114. The period T_s in one example serves to promote an increase in sampling rate, as will be appreciated by those skilled in the art. In one example, the period T_s is less than or equal to $1.125 \times T_{pulse}$. In a further example, the period T_s is less than or equal to T_{pulse}.

The time interval Δt in one example is equal to an even fraction of the period T_{pgc}, (e.g. $T_{pgc}/8$ or $T_{pgc}/16$). In one example, the processor component 112 obtains the plurality of samples S_n starting at a time t_0, with a time interval Δt of $T_{pgc}/8$. For example, the plurality of samples S_n comprise eight samples at t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, $t_0 + 3\Delta t$, $t_0 + 4\Delta t$, $t_0 + 5\Delta t$, $t_0 + 6\Delta t$, and $t_0 + 7\Delta t$. In another example, the processor component 112 obtains the plurality of samples S_n starting at a time t_0 with a time interval Δt of $T_{pgc}/16$. For example, the plurality of samples S_n comprise sixteen samples at t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, $t_0 + 3\Delta t$, $t_0 + 4\Delta t$, $t_0 + 5\Delta t$, $t_0 + 6\Delta t$, $t_0 + 7\Delta t$, $t_0 + 8\Delta t$, $t_0 + 9\Delta t$, $t_0 + 10\Delta t$, $t_0 + 11\Delta t$, $t_0 + 12\Delta t$, $t_0 + 13\Delta t$, $t_0 + 14\Delta t$, and $t_0 + 15\Delta t$.

The processor component 112 employs one or more of the plurality of samples S_n to calculate one or more quadrature terms and one or more in-phase terms. The processor component 112 in one example calculates a set of quadrature terms Q_j, $j = 0$ to y. For example, the set of quadrature terms Q_j comprises a number of quadrature terms equal to ½ a number of samples of the plurality of samples S_n. In one example where the plurality of samples S_n comprises eight samples, y is equal to three, and the processor component 112 calculates the set of quadrature terms Q_j as:

$$Q_0 = S_0 - S_4,\ Q_1 = S_1 - S_5,\ Q_2 = S_2 - S_6, \text{ and } Q_3 = S_3 - S_7 \text{ (FIG. 3).}$$

In another example where the plurality of samples S_n comprises sixteen samples, y is equal to seven, and the processor component 112 calculates the set of quadrature terms Q_j as:

$Q_0 = S_0 - S_8$, $Q_1 = S_1 - S_9$, $Q_2 = S_2 - S_{10}$, $Q_3 = S_3 - S_{11}$,

$Q_4 = S_4 - S_{12}$, $Q_5 = S_5 - S_{13}$, $Q_6 = S_6 - S_{14}$, and $Q_7 = S_7 - S_{15}$ (FIG. 4).

The processor component 112 in one example calculates a set of in-phase terms I_k, $k = 0$ to z. For example, the set of in-phase terms I_k comprises a number of in-phase terms equal to ¼ the number of samples of the plurality of samples S_n. In one example where the plurality of samples S_n comprises eight samples, z is equal to one, and the processor component 112 calculates the set of in-phase terms I_k as:

$I_0 = (S_0 + S_4) - (S_2 + S_6)$, and

$I_1 = (S_1 + S_5) - (S_3 + S_7)$ (FIG. 3).

In another example where the plurality of samples S_n comprises sixteen samples, z is equal to three, and the processor component 112 calculates the set of in-phase terms I_k as:

$I_0 = (S_0 + S_8) - (S_4 + S_{12})$, $I_1 = (S_1 + S_9) - (S_5 + S_{13})$,

$I_2 = (S_2 + S_{10}) - (S_6 + S_{14})$, and $I_3 = (S_3 + S_{11}) - (S_7 + S_{15})$ (FIG. 4).

The processor component 112 employs the set of quadrature terms Q_j to calculate a quadrature term Q_{ab} and a quadrature term Q_s. The processor component 112 in one example calculates the quadrature term Q_{ab} to be equal to a maximum value of absolute values of the set of quadrature terms Q_j:

$Q_{ab} = \max(|Q_j|)$.

The quadrature term Q_{ab} is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art. The processor component 112 calculates a constant C_1 as described herein. The processor component 112 in one example calculates the quadrature term Q_s as:

$$Q_s = C_1 \times \sqrt{\sum_{j=0}^{j=y} Q_j^2} .$$

The quadrature term Q_s is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art.

The processor component 112 employs the set of in-phase terms I_k to calculate an in-phase term I_s. The processor component 112 calculates a constant C_2 as described herein. The processor component 112 in one example calculates the in-phase term I_s as:

$$I_s = C_2 \times \sqrt{\sum_{k=0}^{k=z} I_k^2}\,.$$

The in-phase term I_s is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art. The processor component 112 in one example calculates the constant C_1 and the constant C_2 such that respective absolute values of the quadrature term Q_s, the quadrature term Q_{ab}, and the in-phase term I_s are substantially equal at a modulation depth M of an operating range.

The processor component 112 employs the quadrature terms Q_s and Q_{ab} to calculate a quadrature term Q_m. The processor component 112 in one example employs the quadrature terms Q_s and Q_{ab} to calculate a correction term ΔQ, for example:

$$\Delta Q = Q_s - Q_{ab}.$$

The processor component 112 employs a linear combination of the quadrature term Q_s and the correction term ΔQ to calculate the quadrature term Q_m. The processor component 112 in one example calculates a constant C_3 and calculates Q_m according to a first order linear equation:

$$Q_m = Q_s + (C_3 \times \Delta Q)\,.$$

The processor component 112 calculates the constant C_3 to promote an increase in a maximum variation of the modulation depth M. The quadrature terms Q_{ab} and Q_s and the in-phase term I_s change with respect to the modulation depth M at different respective rates. The changes with respect to the modulation depth M reduce the accuracy of the calculation of

the phase angle φ, as will be understood by those skilled in the art. The correction term ΔQ serves to create the quadrature term Q_m such that the quadrature term Q_m and the in-phase term I_s comprise a substantially equal rate of change with respect to the modulation depth M over an operating range for the phase generated carrier. The substantially equal rates of change with respect to the modulation depth M of the quadrature term Q_m and the in-phase term I_s reduces a sensitivity to a change in the modulation depth M of the calculation of the phase angle φ, as will be appreciated by those skilled in the art.

For example, at a modulation depth M of an operating range for the phase generated carrier, Q_{ab}, Q_s, and I_s are substantially equal and ΔQ is equal to zero. As the modulation depth M deviates from the operating point within the operating range, Q_s and Q_{ab} change with respect to the modulation depth M with different rates. The change in Q_s and Q_{ab} cause a deviation in ΔQ, and subsequently a change in Q_m. A rate of change of Q_m and a rate of change of I_s with respect to the modulation depth M are substantially equal within the operating range, as will be appreciated by those skilled in the art.

The modulation depth M in one example is between 1.0 and 1.7 radians. For example, the modulation depth M is sufficiently large to promote an increase in signal strength of the phase generated carrier 114. The modulation depth M in a further example is sufficiently small to promote stability of the quadrature term Q_s and the in-phase term I_s with respect to a change in the modulation depth M. For example, the modulation depth M is approximately equal to $\pi/2$.

The processor component 112 employs one or more of the set of quadrature terms Q_j and the quadrature term Q_m to calculate a quadrature term Q. The processor component 112 in one example employs a magnitude of the quadrature term Q_m and a sign of one of the quadrature terms of the set of quadrature terms Q_j to calculate Q. For example, the processor component 112 chooses the quadrature term Q_1 that comprises a relatively large magnitude to

avoid a zero crossing of the magnitude. The processor component 112 chooses a different quadrature term with a larger magnitude, for example, the quadrature term Q_0, when the magnitude of the quadrature term Q_1 approaches zero. The quadrature term Q is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art.

The processor component 112 employs one or more of the set of in-phase terms I_k and the in-phase term I_s to calculate an in-phase term I. The processor component 112 in one example employs a magnitude of the in-phase term I_s and a sign of one of the in-phase terms of the set of in-phase terms I_s to calculate I. For example, the processor component 112 chooses an in-phase term I_1 that comprises a relatively large magnitude to avoid a zero crossing of the magnitude. The processor component 112 chooses a different in-phase term, for example, the in-phase term I_0, when the magnitude of the in-phase term I_1 approaches zero. The in-phase term I is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art.

A change in the demodulation phase offset β in one example changes the sign of the quadrature term Q and/or the in-phase term I. Four bands of operation of width $\pi/2$ in one example exist across a total range of 0 to 2π for the demodulation phase offset β. Where the magnitude of the demodulation phase offset β is near a border of a band of operation, the magnitude of the in-phase term I_k chosen to determine the sign of I and/or the magnitude of the quadrature term Q_j chosen to determine the sign of Q may approach zero. When the magnitude of the in-phase term I_k chosen to determine the sign of I and/or the magnitude of the quadrature term Q_j chosen to determine the sign of Q approaches zero, the processor component 112 chooses a different quadrature term Q_j and/or in-phase term I_k. The processor component 112 chooses a different quadrature term Q_j and/or in-phase term I_k to promote the calculation of the phase angle φ independent from the demodulation phase offset β. The phase modulator 106 in one example maintains the demodulation phase offset β within a

range significantly smaller than 0 to $\pi/2$, therefore the demodulation phase offset β does not need to be known, as will be appreciated by those skilled in the art.

The processor component 112 employs the quadrature term Q and the in-phase term I to calculate the phase angle φ independently of the demodulation phase offset β. Since the quadrature term Q and the in-phase term I are independent from the demodulation phase offset β, the calculation of the phase angle φ is independent from the demodulation phase offset β. The processor component 112 in one example calculates the phase angle:

$$\varphi = \text{arctangent}\,(Q / I).$$

The processor component 112 in one example employs the change in the phase angle φ between multiple instances of the interference pulses 130, 132, and 134 to determine the change in the parameters employed by the sensors 124, 126, and 128.

Turning to FIG. 2, the plot 202 comprises an exemplary representation of the interference pulses 130, 132, and 134 and appropriate sampling times for the processor component 112 with respect to time t. The interference pulses 130, 132, and 134 are represented by the analog electrical signal $s(t, M, \beta, \varphi)$. The quadrature and in-phase components of the interference pulses are represented by $s(t, M, \beta, \pi/2)$ and $s(t, M, \beta, 0)$, respectively. One or more square pulses 230, 232, and 234 represent the period T_{pulse} of the interference pulses 130, 132, and 134, respectively. The square pulses 230, 232, and 234 comprise a spacing period of T_{space}. The square pulses 230, 232, and 234 in one example comprise a high duty cycle, for example, the sampling period T_s is substantially longer than the spacing period T_{space}.

The processor component 112 in one example obtains eight samples from the respective interference pulses 130, 132, and 134. The processor component 112 in one example obtains the samples at a constant rate over the period T_s. For example, the processor component 112 obtains eight samples, S_0 through S_7, for the interference pulse 130, discards

the next three samples $S_{discard}$, obtains the next eight samples, S_0 through S_7, for the interference pulse 132, discards the next three samples $S_{discard}$, and so forth.

Turning to FIG. 3, a plot 302 comprises a representation of a set of calculations for the quadrature terms Q_j and the in-phase terms I_k for eight samples of the interference pulse 130. Where eight samples are taken, x = 7, y = 3 and z = 1. The processor component 112 calculates a given term by adding and subtracting a plurality of the samples S_n in a respective row of the given term. The processor component 112 adds or subtracts a sample according to a sign designated in the row/column pair for the given term and the sample. If a sign is not listed for a sample, the sample is not used for the given term. For example, the processor component 112 calculates Q_0 as $+S_0 - S_4$, Q_2 as $+S_2 - S_6$, and I_0 as $+S_0 - S_2 + S_4 - S_6$.

Turning to FIG. 4, a plot 402 comprises a representation of a set of calculations for the quadrature terms Q_j and the in-phase terms I_k for sixteen samples of the interference pulse 130. Where sixteen samples are taken, x = 15, y = 7, and z = 3. For example, the processor component 112 calculates Q_0 as $+S_0$-S_8, Q_1 as $+S_2$-S_9, and I_0 as $+S_0$-S_4+S_8-S_{12}. Turning to FIGS. 3 and 4, patterns of the + and the – signs in one example can be seen for the quadrature terms Q_j and the in-phase terms I_k, respectively. For example, similar patterns can be used to calculate a set of quadrature terms Q_j and I_k for a plurality of samples with a different number of samples.

Turning to FIGS, 5, 6, and 7, plots 502, 602, and 702 comprise a representation of the accuracy of the calculation of the phase angle φ for various methods. The accuracy of the calculation of the phase angle φ is measured by calculating a value $\Delta\varphi$. For example, an output phase angle φ_{out} of the phase generated carrier 114 and an input phase angle φ_{in} of the phase generated carrier 114 are used to calculate:

$$\Delta\varphi = \varphi_{out} - \varphi_{in}.$$

The accuracy $\Delta\varphi$ is shown as a function of the input phase angle φ, with plots for various values of the demodulation phase offset β and the modulation depth M. The accuracy was calculated using MathCAD (Mathsoft Engineering & Education, Inc., Cambridge, MA 02142, http://www.mathcad.com) using a pseudo-random number generator to add a variable amplitude noise to the analog electrical signal s(t, M, β, φ). The variable amplitude noise comprises a peak 0.1% fluctuation with a uniform probability density. For comparison, plots 502, 602, and 702 comprise a same scale with an input phase angle φ between -1.5 radians and 1.5 radians and an accuracy $\Delta\varphi$ within .01 radians and -.01 radians.

Referring to FIG. 5, plot 502 represents the accuracy of a prior art demodulation technique that is dependent on the demodulation phase offset β and the modulation depth M. A mean value of $\Delta\varphi$ for the prior art demodulation technique of FIG. 5 is approximately 2.5 milliradians, where β is varied within .00175 radians about an operating point of .29 radians, and M is varied within .05 radians about an operating point of π radians.

Referring to FIG. 6, plot 602 represents an exemplary accuracy of calculation of the phase offset φ where eight samples are taken (e.g. $x = 7$, $y = 3$, $z = 1$). A mean value of $\Delta\varphi$ for the plot 602 is approximately 4 milliradians, where β is varied between .1 and 1.1, and the modulation depth M is varied within .05 radians about an operating point of 1.63 radians.

Referring to FIG. 7, plot 702 represents an exemplary accuracy of calculation of the phase offset φ where sixteen samples are taken (e.g. $x = 15$, $y = 7$, $z = 3$). A mean value of $\Delta\varphi$ for the plot 702 is approximately 2.5 milliradians, where β is varied between .2 and 1.3, and M is varied within .07 radians about an operating point of 1.6 radians. The plots 602 and 702 comprise a similar accuracy to the prior art demodulation technique of FIG. 5 with a reduced restraint on the demodulation phase offset.

The apparatus 100 in one example employs one or more computer-readable signal-bearing media. One example of a computer-readable signal-bearing media for the apparatus 100 comprises the recordable data storage media 144 of the processor component 112. For example, the computer-readable signal-bearing media for the apparatus 100 comprises one or more of a magnetic, electrical, optical, biological, and atomic data storage media. In one example, the computer-readable signal-bearing media comprises a modulated carrier signal transmitted over a network comprising or coupled with the apparatus 100, for instance, one or more of a telephone network, a local area network ("LAN"), the internet, and a wireless network.

The steps or operations described herein are just exemplary. There may be many variations to these steps or operations without departing from the spirit of the invention. For instance, the steps may be performed in a differing order, or steps may be added, deleted, or modified.

Although exemplary implementations of the invention have been depicted and described in detail herein, it will be apparent to those skilled in the relevant art that various modifications, additions, substitutions, and the like can be made without departing from the spirit of the invention and these are therefore considered to be within the scope of the invention as defined in the following claims.